

ACCEPTABLE REINFORCING STEEL SPLICES FOR BLAST RESISTANT CONCRETE STRUCTURES DESIGNED IN ACCORDANCE WITH TM 5-1300, "STRUCTURES TO RESIST THE EFFECTS OF ACCIDENTAL EXPLOSIONS"

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ABSTRACT

TM 5-1300, "Structures to Resist the Effects of Accidental Explosions", provides the structural engineering criteria for the design of blast resistant concrete structures to meet the performance requirements specified in DOD 6055.9-STD, "DOD Ammunition and Explosives. According to TM 5-1300, mechanical reinforcing splices "must be capable of developing the ultimate dynamic strength of the reinforcement without reducing its ductility". This paper discusses the ability of existing mechanical splices to comply with TM 5-1300 and provides recommendations for revised guidance to supplement the existing criteria.

1.0 Background Information

According to TM 5-1300, section 4-21.8, "Mechanical devices may be used for end anchorage and splices in reinforcement. These devices must be capable of developing the ultimate dynamic tensile strength of the reinforcement without reducing its ductility. Tests showing the adequacy of such devices under dynamic conditions must be performed before these devices are deemed acceptable for use in hardened structures." In this section, the ductility (or ductility ratio) of reinforcement under tension can be defined as the ratio of the reinforcement maximum elongation (elongation at failure) to its elastic elongation (elongation at yield).

Unfortunately, no mechanical splices are currently available which fully satisfy the code requirements. Numerous splicing systems will develop the ultimate dynamic tensile strength of the reinforcement but none of the systems can do so without some reduction in ductility.

In explanation, ASTM A 615 steel is typically used in reinforced concrete construction in the United States. To meet ASTM A 615 tensile requirements, Grade 60 steel must attain a

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minimum elongation under tensile load of between 7% and 9 %, depending upon the bar diameter. Since Grade 60 steel will yield at a strain of approximately 0.2%, these minimum elongations correspond to ductility ratios of between 35 and 45.

Mechanical splices used in conventional concrete construction in the United States are required to satisfy the "Building Code Requirements for Reinforced Concrete" (ACI 318). According to section 12.4.3 of ACI 318-92, full welded splices and mechanical connections must develop at least 125 percent of the specified yield strength of the bar. No ductility requirement is given. Consequently, manufacturers of splices have, until recently, considered only ultimate strength in designing their systems. As a result, ductility ratios for splicing systems have consistently been much lower than those for steel reinforcement.

According to section 4-12.2 of TM 5-1300, ASTM A 615, Grade 60 reinforcing steel has adequate ductility for general use in blast resistant concrete structures. If necessary, reinforcing steel with a minimum yield strength of 75,000 psi may be special ordered, but the code recommends that it only be used in straight bars with splicing avoided. Therefore, in the remainder of this report, discussion is limited to the evaluation of splices of Grade 60 reinforcing bars.

2.0 Literature Search

An extensive literature search was performed. Unfortunately, there was only limited information available on the behavior of splicing systems under dynamic loading. The information developed is summarized in the following paragraphs.

In April 1971, the U.S. Army Waterways Experiment Station issued their report, "Dynamic Tests of Large Reinforcing Bar Splices" by W.J. Flathau. The study was sponsored by the Huntsville Division, U.S. Army Corps of Engineers and had as its primary purpose the evaluation of the effectiveness of butt-weld, Thermit, and Cadweld splicing systems under dynamic loading. All tests used No. 11 reinforcing bars made from ASTM A 615 steel. Tests were conducted on splices of both Grade 60 and Grade 75 reinforcing bars.

A total of 59 tests were conducted. The tests employed three different general rates of strain, denoted in the report as rapid, intermediate, and slow. For the splices of Grade 60 reinforcing steel, eight splices were tested at rapid strain rates (2.2 to 3.25 inch/inch/second), eight splices were tested at intermediate strain rates (0.0057 to 0.0579 inch/inch/second), and nine splices were tested at slow strain rates (0.0021 to 0.0026 inch/inch/second). In comparison, volume 4 of TM 5-1300 assumes reinforcement strain rates of 0.1 inch/inch/second (far design range) and 0.3 inch/inch/second (close-in design range) for concrete members in bending and strain rates of 0.3 inch/inch/second (far design range) and 0.5 inch/inch/second (close-in design range) for concrete members in compression.

For every splice tested, the ultimate strength exceeded 125% of the nominal yield strength. Therefore, all splices satisfy current ACI code requirements. In addition, as with reinforcing bars, the ultimate strength of the spliced bars increased as the loading rate increased.

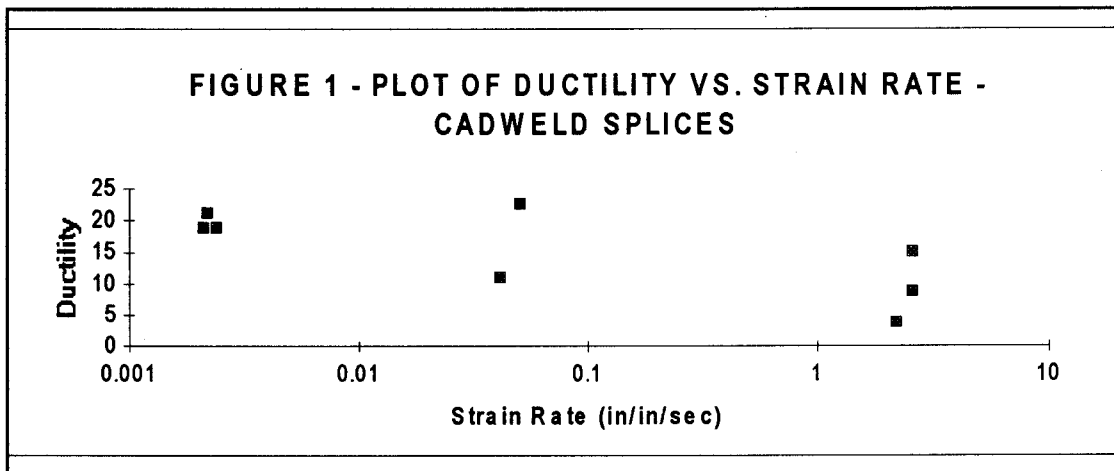
Unfortunately, the splices also exhibited a significant reduction in ductility. The maximum strain achieved by each splice type was only about one-fourth of the strain that was developed in as-rolled and machined bars.

In the report, the use of butt-welded splices was not recommended. The variation in test results for these splices indicated an undesirable inconsistency in strength. In addition, it was felt that quality control would be much better with the Cadweld and Thermit splices.

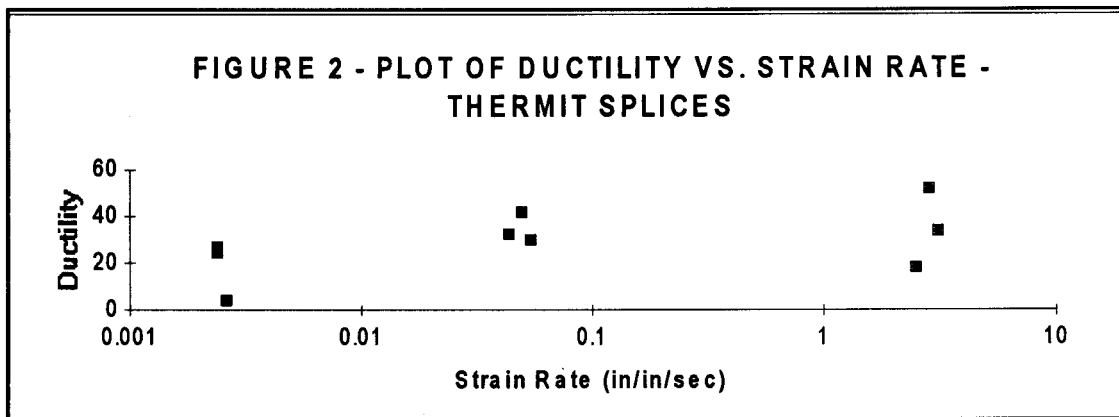
To develop a lower bound on ductility at failure, statistical analysis have been performed on the test data for the Cadweld and Thermit splices. The analyses only use data from splices of Grade 60 reinforcing bars. The ductility of the splices is assumed to follow a normal distribution. Due to the small size of the data sets, a t-distribution is used for both distributions. Results are as follows:

- For the Cadweld splices, the mean ductility is 15.0. Assuming a 90% confidence level, the minimum ductility is 5.6. For a 95% confidence level, the minimum ductility is 2.4.
- For the Thermit splices, the mean ductility is 29.1. Assuming a 90% confidence level, the minimum ductility is 10.1. For a 95% confidence level, the minimum ductility is 3.7.

Plots of ductility versus strain rate are provided in figure 1, for Cadweld splices, and figure 2, for Thermit splices.



**FIGURE1 - PLOT OF DUCTILITY VS. STRAIN RATE -
CADWELD SPLICES**



**FIGURE 2 - PLOT OF DUCTILITY VS. STRAIN RATE -
THERMIT SPLICES**

As noted in section 1.0, conventional concrete structures are designed in accordance with ACI 318. For concrete elements designed for use in nuclear facilities, the requirements of ACI 349, "Code Requirements for Nuclear Safety Related Concrete Structures", must be satisfied. Since these elements may be subjected to rapid dynamic loading in an accident, the code splice requirements are of particular interest in this study.

According to section 12.14.3 of ACI 349, full welded and mechanical splices may be used in nuclear structures provided that they develop in tension at least 125 percent of the specified yield strength of the bar. In addition, mechanical splices must be prequalified for use in construction by satisfying the static tensile strength tests and cyclic test requirements outlined in section 12.14.3.4.1.

Visual inspection of all welded and mechanical splices is required by section 12.14.3.6. If warranted, the Engineer may also require destructive tests on production line splices to verify compliance with the code. Section 12.14.3.7 outlines requirements for staggering of splices. Where staggering is required, no more than one-half of the bars may be spliced in one plane normal to the bars, and the splices must be staggered at least 36 inches.

In Appendix C of ACI 349, special provisions are provided for impulsive and impactive events. According to section C.3.5, the maximum allowable ductility ratio in flexure is 3.0 for loads such as blast and compartment pressurization which could affect the integrity of the structure as a whole. To ensure ductility, the maximum yield strength allowed for steel reinforcement is 60,000 psi.

3.0 Current Research

At the request of ACI Committee 439, a testing program is underway at the University of Kansas to evaluate the performance of reinforcing bar splices under seismic loads. All tests use splices of #8 reinforcing bars. Splices have been provided for testing by all major American manufacturers and by some manufacturers in Europe and Japan.

The test procedure is as follows. A minimum of nine splices are tested for each splicing system. The splices are loaded at a rate of 100,000 pounds per minute. Strains are measured over a 20" gauge length (including coupler). Three different loading regimes are employed; a minimum of three splices are tested under each regime. Additional tests are performed, as necessary, to investigate anomalies in the test results.

In the first loading regime, splices are loaded monotonically to failure. The second loading regime employs 16 cycles to 4% strain followed by loading to failure. In the final loading regime, splices undergo four cycles of loading to 2-1/2% strain followed by four cycles to 3% strain, four cycles to 3-1/2% strain, and four cycles to 4% strain. The splices are then tested to failure.

Thus far, failure modes have varied with some splices failing in the bar, some in the coupler, and others at the bar/coupler interface. Strains at failure have also varied. Splices have

normally failed at strains between 5% and 7%, but some splices have failed at strains as low as 1%. Interestingly, no specimens attaining a strain of 4% under monotonic loading have failed under cyclic loading.

Dr. Steve McCabe, a professor at the University of Kansas, is the current chairman of ACI Committee 439 and is also the project manager for the splice testing program. According to Dr. McCabe, there will likely be some changes to the ACI splice requirements as a result of the test program. In particular, some consideration of minimum allowable ductility in splices is likely. To avoid misuse of strain/ductility measurements, Dr. McCabe also expects guidance in the code as to the length over which strain in a splice will be measured.

4.0 Conclusions

Conclusions are as follows:

- (1) Full mechanical and welded splices should only be allowed for splicing of ASTM A 615, Grade 60 reinforcing bars. In explanation, to provide adequate strength and ductility, Grade 60 reinforcing bars are normally used in blast resistant concrete structures. Commercial splicing systems are designed primarily for the splicing of Grade 60 reinforcing bars. Due to its reduced ductility, splicing of Grade 75 reinforcing bars is not recommended.
- (2) The only available test data for splicing systems subjected to rapid dynamic loading are for the Cadweld and Thermit splicing systems. Both splices satisfy current TM 5-1300 strength requirements, but they also exhibit a considerable reduction in ductility at failure.
- (3) Due to the limited available test data, the 95% confidence levels for ductility of 2.4 for Cadweld splices and 3.7 for Thermit splices may be unduly conservative. In comparison, the nuclear industry assumes a ductility of 3.0 for approved splices of flexural reinforcement under dynamic impulsive loading.
- (4) Since no splicing system can satisfy current TM 5-1300 code requirements, it would appear prudent to revise the present criteria. Test data are available which support the use of Cadweld and Thermit splicing systems in low ductility regions of blast elements. In addition, Cadweld splices have been used extensively in nuclear power plant construction. According to a 1983 report prepared for the U.S. Nuclear Regulatory Commission (NRC), the Cadweld system is the only splicing system approved by the NRC for general use in nuclear power plant construction.
- (5) In accordance with ACI 439 and as discussed in section 4-64 of TM 5-1300, splices of reinforcing bars in blast resistant concrete structures should be staggered and should not be placed in high stress regions. Additional criteria should be added to TM 5-1300 requiring that all mechanical splices be visually inspected by a qualified and experienced inspector with destructive tests performed on production splices, as necessary, to ensure that strength and ductility requirements are met.

(6) There is insufficient information available to evaluate the general use of other splicing systems in blast resistant concrete structures. Through analysis of the results of the University of Kansas splice test program, some of these splices may, in the future, be certified for general use. Therefore, it is recommended that an analysis be performed on the University of Kansas test results following completion of testing. In this analysis, the tested splicing systems can be assessed for general use in blast resistant concrete structures.

5.0 Recommendations

Based on the report conclusions, the following revisions to TM 5-1300 are recommended (changes are underlined and italicized):

4-21.8 Mechanical Splices of Reinforcement

Mechanical splices may be used for end anchorage and splices in ASTM A 615 Grade 60 reinforcement. These devices must be capable of developing the ultimate dynamic tensile strength of the reinforcement and must achieve the ductility assumed in the design of the structural member. Tests showing the adequacy of such devices under dynamic conditions must be performed before these devices are deemed acceptable for use in hardened structures. In lieu of prequalifying testing, Cadweld splices may be used for members designed to attain an elastic response or slightly plastic response (X_m/X_E less than or equal to 3.0).

4-64. Flexural Reinforcement (Paragraph 6)

Mechanical splices may also be used, but they must be capable of developing the ultimate strength of the reinforcement and must achieve the ductility assumed in the design of the structural member. If the bar deformations have to be removed in the preparation of these splices, grinding rather than heat should be employed since heat can alter the chemical properties thereby reducing the capacity of the element. Welding of the reinforcement should be prohibited unless it can be determined that the combination of weld and reinforcement steel will not result in a reduction of the ultimate strength or in an inability to provide the required ductility. In those cases where welding is absolutely essential, it may be necessary to obtain special reinforcement manufactured with controlled chemical properties, such as ASTM A706 steel reinforcement.

All mechanical splices shall be visually examined by a qualified and experienced inspector to assure that they are properly installed at the place of construction. Where it is deemed necessary, the inspector or engineer may require destructive tests of production splices to assure compliance with this section and Section 4-21.8.

6.0 Acknowledgements

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